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Classification of geothermal resources in Poland by exergy analysis—Comparative study

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ABSTRACT

Geothermal resources in Poland are of growing importance for the production of renewable energy. The total installed geothermal capacity (including heat pumps) at the end of 2008 was ca. 281 MW_t, while heat sales about 1501 TJ. Poland is characterised by low-temperature geothermal resources connected mostly with the Mesozoic sedimentary formations. In the paper the estimation of thermodynamic potential of Polish geothermal fields in comparison with selected global resources was presented. Geothermal resources were classified with reference to their specific exergy and specific exergy index (SEI). These indices define the quality of the energy content of a geothermal fluid better than conventional temperature criterions.

Contents

1. Introduction

The review of geothermal energy technology and global status of geothermal energy utilization were presented by Barbier [1] and Fridleifsson [2]. Poland, despite considerable geothermal resources, was not included in these publications due to relatively new interest in using geothermal energy, which was the result of traditional approach to national energy industry mainly based on coal.

Geothermal use for heating purposes in Poland was initiated in the last decade of the 20th century. The experimental stage of the first geothermal plant was opened in the Podhale region (foredeep of Tatra Mountains, Fig. 1) in 1992 [3]. Since that time five other plants have been launched for space heating which is a key sector for geothermal in Poland. It is also worth noticing that the interest in recreation and balneotherapy is growing. Seven new centres were opened in recent years.

In some cases geothermal energy is proposed not only as exclusive energy source but also in combination with other renewable or traditional energy sources.

Like in other countries, the studies and first R&D started on the possibility to produce electricity in binary schemes using ca. 90–120 °C waters. Wide-range use, adequate for the reservoir potential, would permit us to locally limit reliance on fossil fuels and mitigate the GHGs and other emissions. Other types of use include greenhousing, wood drying and fish farming, salt extraction from geothermal water.

Over the last several years some general documents related to the energy policy of the country were introduced, e.g. the Strategy of Energy Policy in Poland until 2030, and in 2009 – the EU Directive on the promotion of RES (Renewable Energy Sources) [4].

According to these documents the share of all RES, including geothermal, in final energy use (electricity plus heat & cold plus biofuels) shall reach 15% in Poland by 2020. These figures seem to be significant as compared to the current share of all RES in energy generation (ca. 7%).

As one of the main RES in Poland, geothermal should be promoted regarding the requirements the country has to meet as a

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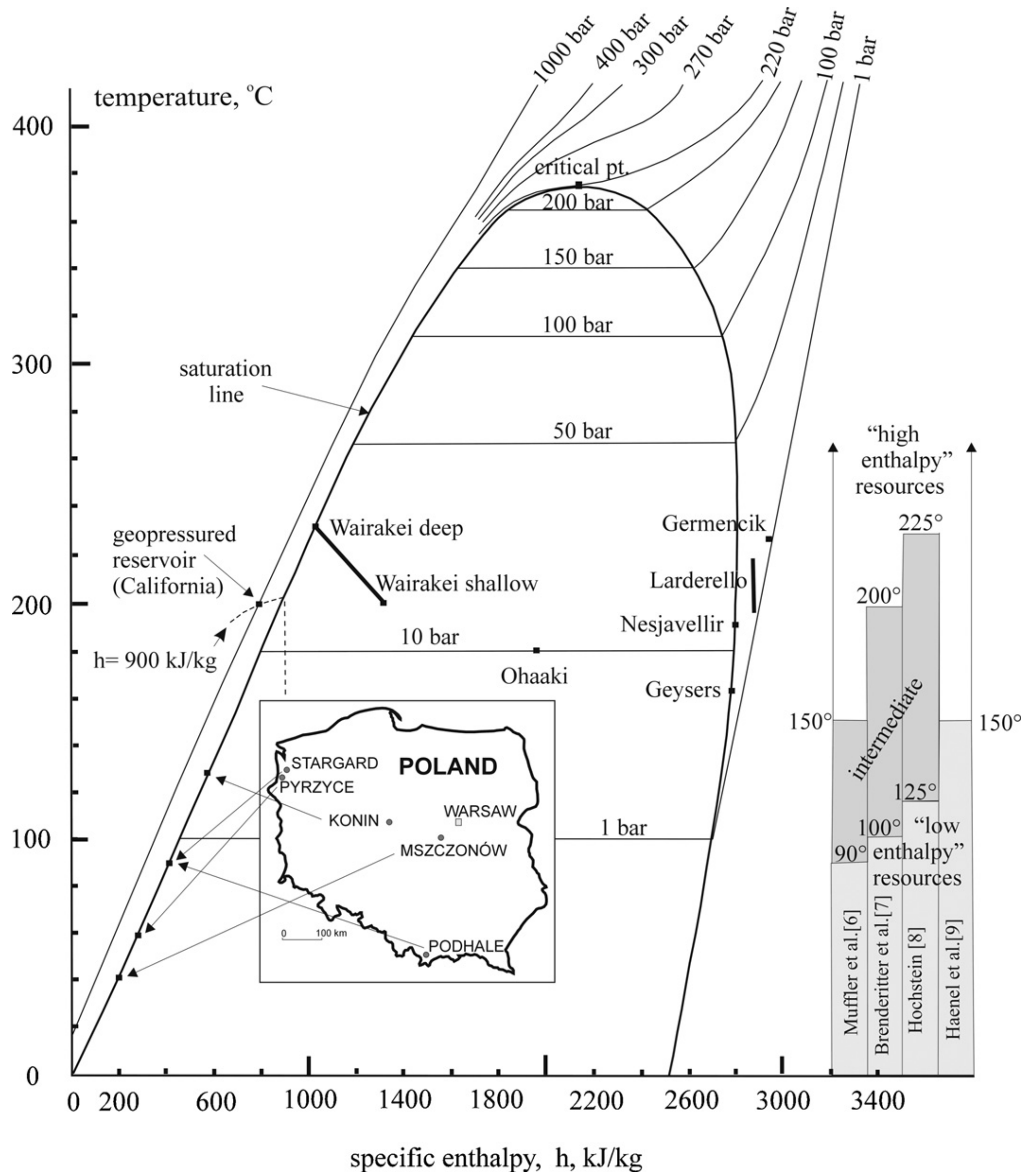

Fig. 1. Geothermal resources of Poland and selected global fields plotted on the enthalpy–temperature diagram as against conventional temperature classification (average wellhead parameters of global fields after: Lee [10], Bettagli et al. [12], Etemoglu et al. [13], Reykjavik Energy [14]).

member of the EU. More favorable legal regulations as well as economic and fiscal incentives shall be introduced. These would serve as the tools to facilitate the geothermal deployment. In 2007–2009 some changes and amendments to ease geothermal investments were introduced in the proposal of new geological and mining law as well as new provisions of economic support from public sources.

2. Geothermal plants already operating in Poland

The technological solutions adopted in geothermal heating plants in Poland are customised to the differences in hydrogeological properties and chemical characteristics of the thermal aquifers, the level of heat demand and temperature parameters which that depend on the type of end-user.

The geothermal heating plants in Pyrzyce (installed capacity 48 MW_t) and Mszczonów (installed capacity 10.2 MW_t) (Fig. 1) meet end-user needs by utilizing geothermal resource and backing-up gas boilers. The systems operating in these two plants consist of combined heat pumps of the absorptive type (AHP) and low-temperature gas-fired boilers, which are used at peak load on the coldest days when heat pumps cannot generate enough heat to meet end-user needs. In the geothermal plant in Pyrzyce there are two AHP units of 10 MW each, while in Mszczonów there is a capacity of 2.7 MW [5].

As mentioned before, the geothermal plant in Mszczonów consists of an Sanyo absorption heat pump, low-temperature boilers used at peak-load, and a high-temperature boiler. The heat source for the pump is the thermal water produced by the well, at a flow-rate of 55 m^3/h and temperature of 42 °C. After cooling, the thermal water is used for drinking purposes and the remainder is discharged into surface streams (single-well arrangement).

The heating system in the Podhale Trough consists of a thermal water source, gas-fired boilers used at peak load, and units generating both heat and electric energy (co-generator unit) from natural gas. This is thought to be one of the biggest geothermal projects in Europe, at an estimated cost of about US$ 100 million. The target capacity of the plant constructed as part of this project is 125 MW (93 MW_t of which will come directly from thermal waters), with

an energy output of 1.2 million GJ per year. The project will cover an area of about 70 km^2. In 2008 a part of geothermal water cooled down in heat exchangers started to supply a new bathing centre ("Termy Podhalańskie").

The differences in the technological solutions for these three plants are mainly dictated by the temperature of the thermal waters. The Podhale waters reach temperature of about 90 °C, while those in Pyrzyce and Mszczonów have temperatures of 61 °C and 42 °C, respectively.

The plant in Stargard (Fig. 1) was open in 2006 with geothermal capacity 10 MW_t extracted by heat exchangers (water temperature 87 °C) serving about 75% local population (70,000).

There are also geothermal plant in Uniejów town (central Poland) opened in 2001 (capacity 5.6 MW_t) and seven geothermal bathing centres constructed after 2000 y.

In the future geothermal plant in Konin (Fig. 1) is planned to exploit thermal waters of Lower Jurassic aquifer where reservoir temperatures reach up to 130–140 °C (binary power plant).

Also, the market for shallow geothermal heat pumps, GHPs, has been constantly growing. On a basis of available data and market analyses one may very roughly assume the total installed capacity is at least 180 MW_t and heat production 1000 TJ/2008. About half of newly installed GHPs has capacities less than 70 kW, larger capacities (70–110 kW) form ca. 30% of installations while bigger ones (110–150 kW) are not common.

These facts resulted in the total level of ca. 281 MW_t of installed geothermal capacity and 1500 TJ/2008 of heat use for the whole country at the end of 2008 as compared to the level of 170 MW_t and 838 TJ in 2004 [4].

The issues presented in the article not only allow the assessment of Polish geothermal resources in energy terms, compared to the world resources, but also the estimation of the quality of the energy content of a geothermal waters by an exergy.

3. Classification of geothermal resources by temperature and enthalpy

Thermodynamic classification of geothermal resources alone does not settle a question whether to built a geothermal plant (required technical and economic analysis take into account the total fluid mass and total capacity), but plays an important part in qualitative definition of geothermal resources by their ability to do work.

The most popular classification of geothermal resources is held by the assessment of the temperature of geothermal fluids, referring to their enthalpy at the same time ([6–9] in Fig. 1).

However, Lee [10] states that classification of geothermal resources by their temperatures or enthalpies alone is inconsistent and confusing. The simplified formulas for specific enthalpy, h, are:

$$h \approx c^w t + pv \text{(for water zone, in relation to } 0\,^\circ\text{C)} \quad (1)$$

$$h = h^{sw} + xr \quad \text{(two-phase zone)} \quad (2)$$

$$h = h^{ss} + c^s \Delta t \,\text{(steam zone)} \quad (3)$$

where p is the pressure (bar), c^w is the average specific heat of water (kJ/kg K), c^s is the average specific heat of steam for constant p (kJ/kg K), t and Δt are the temperature and temperature increase, respectively (°C), v is specific volume (m^3/kg), h^{sw} and h^{ss} are the specific enthalpy of saturated water and saturated steam, respectively (kJ/kg), x is the degree of dryness and r is the specific heat of vaporisation (kJ/kg).

In Fig. 1 there is a diagram h–t for different pressures for water and steam with the situation of Polish and world geothermal fields on this background. The situation of resources in the diagram is approximate, because, as Kestin proved [11], taking into account mineralization and/or gasification of thermal waters can change the values of thermodynamic parameters above 7% for brines and above 17% for liquids gasified with CO_2. Fig. 1 shows also conventional temperature classifications of geothermal resources after Muffler and Cataldi [6], Benderitter et al. [7], Hochstein [8] and Haenel et al. [9].

As it is shown in Fig. 1, Wairakei deep field (New Zealand [10]), according to temperature criterion, can be classified as "high enthalpy" resource according to its temperature, while Nesjavellir (Iceland [14]) and Geysers (USA [10]), which are characterised by decisively higher enthalpy, as "intermediate enthalpy" resources (after classification of Benderitter et al. [7] and Hochstein [8]). On the other hand, Wairakei shallow and geopressured reservoir would be qualified "intermediate enthalpy" resources, thus the same quality as Nesjavellir, despite the fact that it shows much higher enthalpy (energy of steam).

So referring to enthalpy at the classification temperatures is confusing, because enthalpy is not only related to temperature, but also significantly depends on the phase of the liquid (compare formulas (1)–(3)).

However enthalpy alone does not make a good index of energy quality of geothermal resources. Taking into account Geysers and Nesjavellir (Fig. 1), one can see that the values of enthalpy of both resources can be similar (on average about 2800 kJ/kg), however, in energy terms, Nesjavellir looks more favorable due to higher temperature.

Compared to well known Italian (Larderello), Icelandic, Turkish (Germencik), New Zealander, American and Japanese (Otake, Fig. 2) geothermal resources – Polish geothermal resources in energy terms look much more modest. Only in the central area of Poland there are local conditions for the production of electricity in binary systems, and geothermal resources can be classified as intermediate resources (Konin, Fig. 1).

4. Classification of geothermal resources by exergy

Lee in 2000 [10] introduces an energetic parameter that describes unambiguously the thermodynamic state of geothermal fluids i.e. *exergy*, as the maximum work available. To analyse a geothermal power plant, the concept of exergy was first used by Bodvarsson and Eggers [15]. After Lee [10] in the proposed methodology of classification, the following is accepted: fluid definition point at the wellhead, triple point of water as the sink condition (datum), specific exergy as quality of resource for unit mass of fluid, and boundary conditions of classification as: wellhead temperature 100 °C and wellhead pressure 1 bar.

The specific exergy, e, is calculated as:

$$e = h - h_0 - T_0(s - s_0) \quad (4)$$

where h is the specific enthalpy (kJ/kg), s is the specific entropy (kJ/kg K), T is the absolute temperature (K) and T_0, h_0, s_0 are the parameters of sink conditions.

For sink conditions of triple point ($T_0 \sim 273$ K, $h_0 = 0$ kJ/kg, $s_0 = 0$ kJ/kg K) Eq. (4) takes a simple form:

$$e \approx h - 273s \quad (5)$$

Fig. 2 presents the shown in Fig. 1 diagram h–t on which one put the calculated according to formula (5) specific exergy values and, like in Fig. 1, situated on this background and well known Polish and world's geothermal fields.

As shown above, the diagram presented in Fig. 1 not always gives the opportunities to assess according to the enthalpy, which geothermal resources are energetically better e.g. Geysers or Nesjavellir. Now, we can see in Fig. 2, that Geysers has average specific exergy about 900 kJ/kg and Nesjavellir about 1000 kJ/kg.

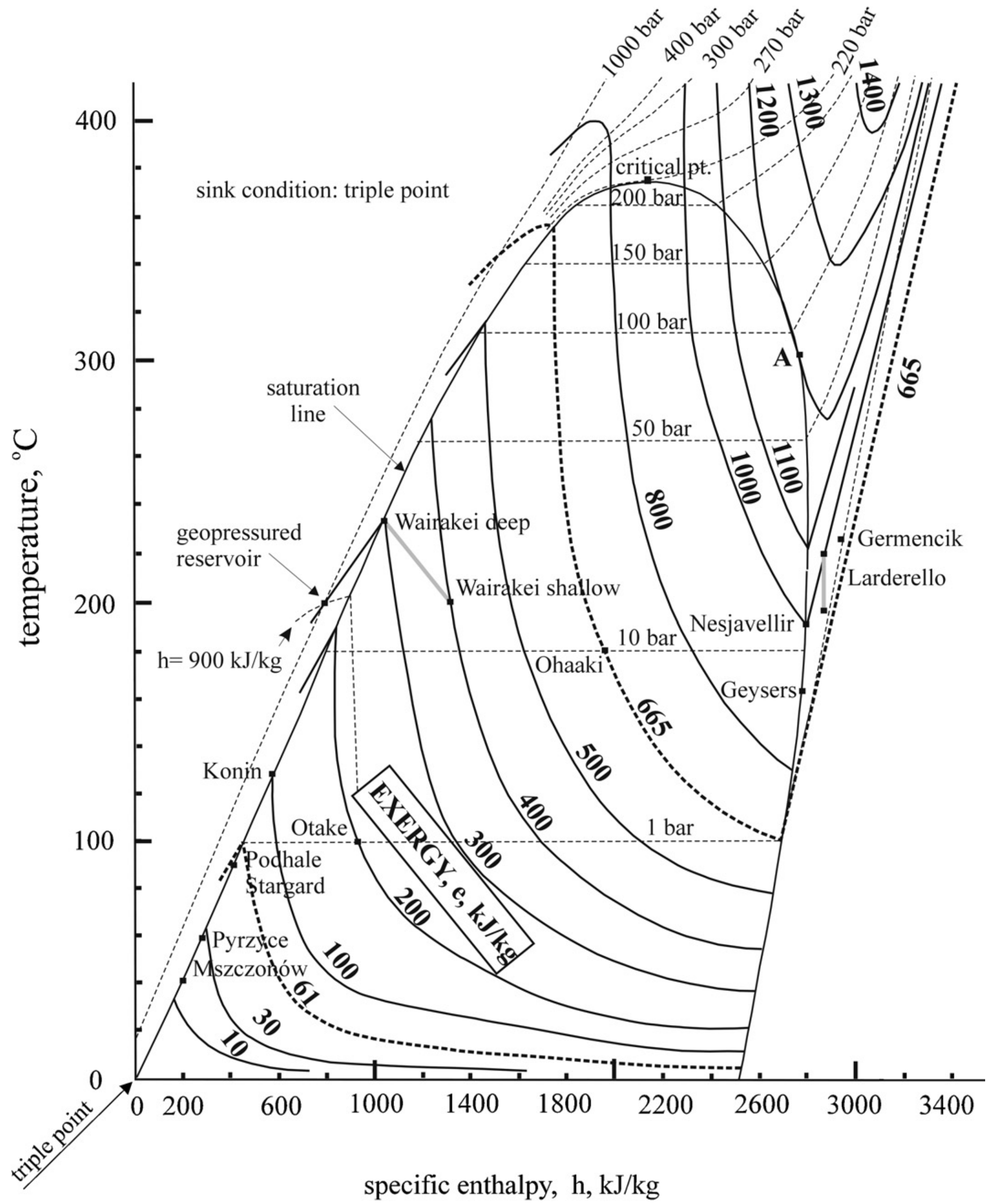

Fig. 2. Geothermal resources of Poland and selected global fields plotted on the enthalpy–temperature–exergy diagram (average wellhead parameters of global fields after: Lee [10], Bettagli et al. [12], Etemoglu et al. [13], Reykjavik Energy [14]).

The image Fig. 1 also suggests that Germencik from a thermodynamic point of view is better as Nesjavellir (higher temperature and enthalpy). However, in exergy terms, with the accepted here wellhead parameters (Nesjavellir: $p \approx 12$ bar, $T \approx 190\,^{\circ}$C, Germencik: $p \approx 3$ bar, $T \approx 225\,^{\circ}$C) Germencik has less exergy (about 920 kJ/kg).

Following Lee [10] we can assume that specific exergy of 100 °C saturated water at 1 bar, i.e. 61 kJ/kg, is the upper limit for low quality resources. On the other hand, specific exergy of saturated steam at 1 bar and 100 °C, i.e. 665 kJ/kg (the lowest exergy of steam that can be used for the direct generation of electricity), can be assumed as lower limit for high quality resources. Medium quality resources therefore would have the value of specific exergy between 61 and 665 kJ/kg, as shown in Fig. 2.

Polish geothermal resources, in the definite majority, would belong to the group of low quality resources and only resources of the Konin area could be regarded as medium quality resources (about 100 kJ/kg).

Classification of geothermal resources by exergy is more consistent and technically meaningful than the one bases on their temperature and enthalpy, but values of the specific exergy are sensitive to sink condition. To diminish the influence of sink conditions, the exergy can be normalized by the maximum exergy described for points of saturated line for corresponding sink condition [10].

The classification of geothermal resources by quality indicator defined as SEI = e/e_{max} (Specific Exergy Index) will be almost independent on assumed sink condition.

In presented diagram (Fig. 2), specific exergy values vary on saturated line from 0 to 1192 kJ/kg for triple point condition (e_{max} = 1192 kJ/kg, point A in Fig. 2 – saturated steam at 90 bar). The normalization of the values of specific exergy accepted as border values in the classification of geothermal resources for triple

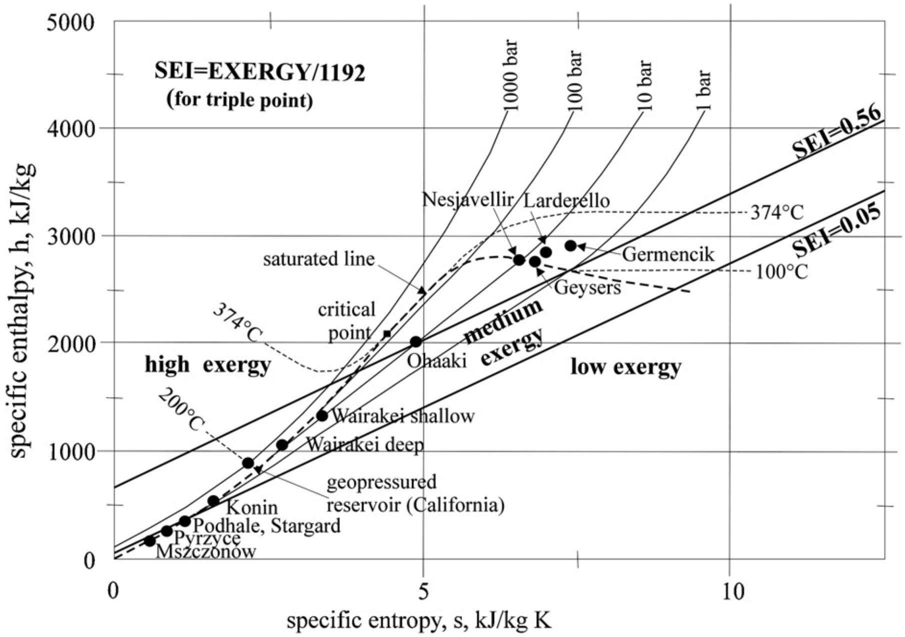

Fig. 3. Classification of geothermal resources by SEI in Poland and selected global fields plotted on Mollier diagram (average wellhead parameters of global fields after: Lee [10], Bettagli et al. [12], Etemoglu et al. [13], Reykjavik Energy [14]).

point condition (61 and 665 kJ/kg), gives border values SEI = 0.05 and 0.56.

Taking into account that

$$SEI = \frac{[h - h_0 - T_0 (s - s_0)]}{e_{\max}} \tag{6}$$

a function $h(s)$ is linear for any accepted sink conditions (T_0, h_0, s_0) and established value SEI. Thus drawing two separation lines $h(s)$ for SEI = 0.05 and 0.56 on an (h–s) plot of Mollier diagram gives the possibility of the classification of geothermal resources without the need of counting the exergy, and only based on known enthalpy and entropy (Fig. 3).

According to the proposal by Lee [10] geothermal resources in the area above SEI = 0.5 are the high exergy (quality) resources, in the area below SEI = 0.05 are the low exergy resources and in the area between are the medium exergy resources.

The majority of Polish geothermal resources are low exergy resources: Stargard and Podhale SEI = 0.046; Pyrzyce SEI = 0.02; Mszczonów SEI = 0.016 and only resources of the area of Konin could be counted among the medium exergy resources SEI = 0.08 (Fig. 3).

5. Conclusions

1. The variety of reservoir condition in Poland proves the variety of possibilities in which geothermal energy can be used, adjusted to local conditions and needs. Growing interest has been observed specially in geothermal bathing sector which attracts private investors. Systems based on deep hydrothermal resources, as well as on shallow groundwater and rock formations, are successfully exploited.
2. Classification of geothermal resources by temperature referring to enthalpy (e.g. 90° – low enthalpy resources), is correct *only* for hot water resources, where enthalpy is almost a linear function of temperature. Many geothermal resources in *reservoir* conditions are hot and warm water and for them the classification based on reservoir temperatures can be applied (e.g. in Poland).
3. If the fluid definition is established as the point at the wellhead, where we have water, two-phase medium or steam, for classify the thermodynamic state of a fluid two independent thermodynamic properties are required (e.g. enthalpy and entropy).
4. The enthalpy values alone do not to be a good parameter for the classification of geothermal resources. The better criterion is an exergy as the function of enthalpy and entropy, but it is dependent of the sink conditions. The normalization of exergy gives, as a result of powerful indicator SEI independent from sink conditions.
5. The presented classification of geothermal resources alone does not settle a question whether to built a geothermal plant (required technical and economic analysis). That is the thermodynamic classification where we define different geothermal resources *qualitatively* by their ability to do work by the mass unit of fluid. When we compare two geothermal resources in order to find the "better" for an investment, we have to describe them also quantitatively taking into account total fluid mass (yield of reservoir), total capacity, cost of drilling and so on.
6. Polish geothermal resources according to SEI look much more modest than, world geothermal fields. However, assessing quantitatively the significant yields of aquifers (e.g. in Podhale up to 800 m^3/h for one-well) allow their wider and wider application in the economically profitable way. The area of Konin (central Poland) is planned to become the first in Poland geothermal binary power plant.

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